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S. Nemat-Nasser, Principal Investigator



. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
University of California, San Diego
Department of Applied Mechanics and Engineering
9500 Gilman Drive
La Jolla, California 92093-0411

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This report outlines instruments acquired and fabricated at UCSD, under Grant No. DAAL03-88-G-0007, as part of the URI on Ultrahigh Dynamic Performance Materials. The URI was awarded by ARO in October, 1986. The instrumentation developed under this grant includes a computer control system for safe operation of gas gun; dedicated interferometry recording system for gas gun; an ultrasonic system; a 300kV flash X-ray system; an image-converter camera system capable of 20 million frames per second; a high-speed framing and streak-recording camera capable of up to two million frames per second, 85 high-resolution frames; a complete image-processing system dedicated to dynamic quantitative holography; and necessary dedicated wave-form digitizers. In addition, a novel system is developed to generate laser-induced high amplitude, short duration stress pulses, using much of the facilities which already existed at UCSD.

Included in this report is a brochure entitled "The Experimental Facilities of the Center of Excellence for Advanced Materials" which includes brief descriptions and photographs of many of the instruments reported herein.

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# FINAL TECHNICAL REPORT

for the period

January 4, 1988 to December 31, 1991

on

## Instrumentation for Ultrahigh Strain Rate Experiments

Grant No. DAAL03-88-G-0007

Dr. S. Nemat-Nasser, Principal Investigator
University of California, San Diego, La Jolla, California 92093

### Table of Contents

## ABSTRACT

This report outlines instruments acquired and fabricated at UCSD, under Grant No. DAAL03-88-G-0007, as part of the URI on Ultrahigh Dynamic Performance Materials. The URI was awarded by ARO in October, 1986. The instrumentation developed under this grant includes a computer control system for safe operation of gas gun; dedicated interferometry recording system for gas gun; an ultrasonic system; a 300kV flash X-ray system; an image-converter camera system capable of 20 million frames per second; a high-speed framing and streak-recording camera capable of up to two million frames per second, 85 high-resolution frames; a complete image-processing system dedicated to dynamic quantitative holography; and necessary dedicated wave-form digitizers. In addition, a novel system is developed to generate laser-induced high amplitude, short duration stress pulses, using much of the facilities which already existed at UCSD.

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# 1. INTRODUCTION

Since October, 1986, the Center of Excellence for Advanced Materials, with focus on ultrahigh strain rate deformation regimes, has been established at the University of California, San Diego (UCSD), by ARO as a part of the DoD's University Research Initiative (URI). The aims of this multidisciplinary Center are:

A. To develop, through coordinated experimental, theoretical, and computational methods, the scientific and technological know-how for analysis and design of advanced materials with tailored microstructures which will have desired macroscopic properties under ultrahigh rates of straining.

B. To provide a high-quality intellectual atmosphere for doctoral and post-doctoral advanced education in an integrated materials engineering program with strong input from materials science, mechanics and applied mathematics, computational mechanics, and shock physics.

C. To provide a forum for scientific exchange and research and collaborative work among advanced students and scientists selected from various universities, UC-National Laboratories, Army Laboratories, and Industry.

The Center focuses on three major and interrelated scientific areas:

1) *Materials:* This includes microstructural characterization of undamaged and damaged materials, examination of the effects of metallurgical variables on the mechanical response, macromechanical characterization through experiments in controlled environments, and materials design.

2) *Modeling and Computation:* This includes micromechanical modeling of nonlinear response and failure modes, constitutive characterization of the materials at high and ultrahigh strain rates, the associated computer algorithms to be used in large-scale computer programs, and numerical experimentation and computer prediction of material behavior under ultrahigh strain rates.

3) *Dynamic Tests*: This includes high and ultrahigh strain-rate experiments on specific advanced materials with controlled microstructures, using flyer-plate, Hopkinson bar, and high-energy laser facilities; this requires new developments in the diagnostics of high strain-rate experiments through high-speed flash photography, X-ray photography, and innovative holography.

The Center has initiated contact with scientists at Los Alamos National Laboratory(LANL), Lawrence Livermore National Laboratory (LLNL), and a number of Army Laboratories, with the specific purpose of cultivating scientific collaboration with scientists of common interest, and, in this manner, utilizing their expertise, as well as some of the unique testing facilities that exist at these important national institutions. At the same time, the Center has embarked on developing dynamic testing facilities which are unique in capability and which, while not as powerful in, for example, attaining projectile speed or size, as those available in the abovementioned national laboratories, are especially designed to attain complex stress and strain regimes in the samples at high strain rates. These instruments include:

1) a large gun capable of propelling up to 500g projectiles up to 1km/sec velocity, its special character will be the capability to produce an oblique impact, hence axial as well as shear straining of the specimen at high strain rates becoming possible;

2) a small gas gun for oblique plate-impact experiments (velocities up to 200 m/s);

3) compression, tension, and torsion Hopkinson bars capable of full recovery experiments in compression, in tension, and in compression followed by tension;

4) laser-induced stress-pulse system for high amplitude, short duration loading.

The above instruments have provided powerful facilities for fundamental work on the basic understanding of material response and failure modes at high strain rates and under general multiaxial dynamic stress conditions. In this sense, they are unique. They are employed in conjunction with and, in fact, complementary to, the important facilities that exist at national laboratories whose scientists have been collaborating participants of the Center.

## 2.0 INSTRUMENTS ACQUIRED OR FABRICATED UNDER THIS AWARD

### 2.1 Grating and Alignment System

*Function:* Traverse displacement measurements in high rate pressure shear equipment

*Major Equipment:*

NuArc ultra-violet exposure system
Optical components
Electronic components

### 2.2 Dedicated Interferometry Recording System

*Description:* Multi-channel waveform digitizing system with computer control and necessary signal conditioning and accessories.

*Major Equipment:*

LeCroy High Speed Transient Digitizer System
Computer Control System
Coherent Innova 70-3 argon ion laser system

### 2.3 Ultrasonic Analysis System

*Description*: This system consists of the Matec system Model #8040, associated transducers, IBM AT compatible computer and components to configure the system into a precision scanning ultrasonic measuring and analysis system.

*Function:* Ultrasonic characterization of materials

*Major Equipment:*

Matec pulse modulator, receiver, plug-ins, filters, attenuators
Panametrics Videoscan (accessory to ultrasonic system)
IBM-AT compatible
Panametrics ultrasonic transducers

### 2.4 Image Converter Camera System

*Function:* High speed framing and streak recording of high strain rate events.

*Major Equipment:*

Hadland Imacon 792 Image convertor camera system*
Optical components
Electronic components

*[refer to page 10 of enclosed brochure for photograph]*

### 2.5 Improved High Speed Imaging Data Acquisition System

*Function:* Ultra high speed Ellis photography, multiple pulse holography, and interferometric shock studies

*Major Equipment:*

Cordin 330A rotating mirror high speed camera system*
Safari Systems' image processor, convolver and camera systems*

*[refer to page 13 and page 17 of enclosed brochure for photograph]*

### 2.6 Oscilloscope and Data Recording System

Nicolet 4094/B Digital Oscilloscope (UCSD Matching Funds)*
Nicolet 4094/C Digital Oscilloscope (UCSD Matching Funds)*
Tektronix 7844 400 Mhz Dual Beam Oscilloscope (UCSD Matching Funds)
Tektronix RTD710 Waveform digitizer. (UCSD Matching Funds)

*[refer to page 11 of enclosed brochure for photograph]*

### 2.7 Flash X-ray System

Link Analytical backscatter electron detector
Golden Engineering radiographic film processor
Hewlett Packard flash X-ray system

### 2.8 *Computer Data Systems*

San Diego Supercomputer compile system
Sun Microsystem computer data system
IBM PC compatable with math coprocessor

## 3.0 SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT

For the fabrication, and set-up, as well as software development design, the following technical individuals have received partial support under this grant:

**Principal Investigator:** S. Nemat-Nasser (UCSD support only)

**Research Engineers**

| | |
|---|---|
| Dr. John E. Starrett, Principal Development Engineer | 7/88 - 5/11/90 |
| Mr. Jon Isaacs, Development Technician III | 7/88 - 12/30/90 |
| Assistant Development Engineer, | 1/1/91 - 12/31/91 |
| Mr. David Lischer, Development Technician II | 6/6/89 - 2/28/91 |
| Jr. Development Engineer | 3/1/91 - 12/31/91 |
| Mr. Douglas Moore, Development Technician II | 7/88 - 12/89 (partial support) |
| Mr. John Haughdahl, Principle Electronic Technician (part-time) | 12/13/90 - 12/31/91 |

**Engineering Aids (Undergraduate Students)**

| | |
|---|---|
| Mr. Brett Ellman, Engineering Aid I | 1/1/90 - 9/18/90 |
| Mr. Ethan Miley, Engineering Aid I | 12/23/90 - 6/30/91 |
| Mr. Ismael Rodriquez, Engineering Aid 1 | 6/27/90 - 9/28/90 |
| Mr. Norman Tang, Engineering Aid I | 12/23/90 - 6/22/91 |

ARO 25786.1-MS-A

a Part of the Final Report

# The Experimental Facilities

## of

## *The Center of Excellence for Advanced Materials*

University of California, San Diego

La Jolla, California

# The Experimental Facilities

of

# *The Center of Excellence for Advanced Materials*

October 1990

Center of Excellence for Advanced Materials
4208 Engineering Building Unit I, 0411
University of California, San Diego
9500 Gilman Drive
La Jolla, California 92093-0411

619-534-5930
Fax: 619-534-7078

## TABLE OF CONTENTS



d/J/ceam2/=m

# I. Introduction

The Center of Excellence For Advanced Materials (CEAM) has grown from the Center for Dynamic Performance of Materials which was established at the University of California, San Diego (UCSD) by the U.S. Army Research Office in October 1986, and currently constitutes the major part of CEAM. The Center focuses on three interrelated scientific areas:

- **Materials**

  Includes microstructural characterization of undamaged and damaged materials, examination of the effects of metallurgical variables on the mechanical response, macromechanical characterization through quasi-static experiments in controlled environments, and materials development, including rapid solidification, chemical synthesis, and self-propagating high-temperature synthesis.

- **Modeling and Computation**

  Includes micromechanical modeling of nonlinear response and failure modes, constitutive characterization of the materials over a broad range of strain rates, including high and ultrahigh rates, the associated computer algorithms to be used in large-scale computer programs, and numerical prediction of material behavior over a broad range of strain rates.

- **Dynamic Tests**

  Includes quasi-static, and high- and ultrahigh-strain rate experiments on specific advanced materials with controlled microstructures using multi-axial testing machines, Hopkinson bar, flyer plate, and high-energy laser impact facilities. This has resulted in new developments of dynamic recovery testing techniques and in the time-resolved diagnostics of high-strain rate experiments through high-speed flash photography, X-ray photography, and innovative holography.

The remainder of this booklet summarizes the experimental facilities currently available at CEAM with special emphasis on the dynamic testing facilities.

## II. Dynamic Testing Facilities

Dynamic testing facilities include Hopkinson bars, gas guns, electromagnetic loading facilities, and a unique laser impulse facility. These instruments have been designed and chosen to provide the range of experimental capability required to support the scientific focus of the Center. They include unique innovative features for **recovery** experiments.

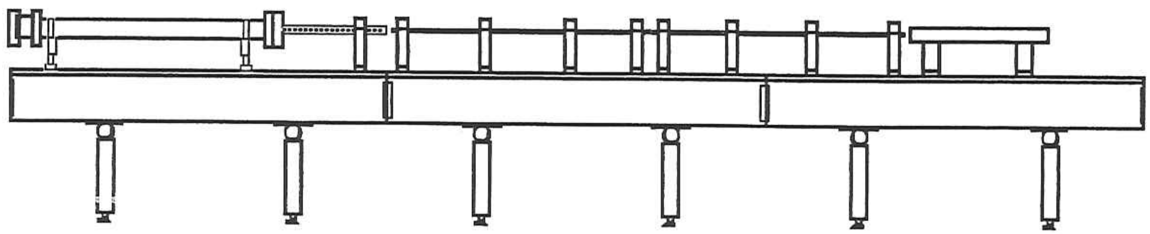
### *Hopkinson Bars*

The split Hopkinson bar apparatus is used to conduct tests to obtain stress-strain data at high rates for materials in simple states of homogeneous stress. The flexible, modular designed bars include:

- Compression
- Tension
- Compression/Tension
- Tension/Compression
- Torsion

UCSD's Hopkinson bar techniques include several novel features for **recovery** experiments and dynamic Bauschinger studies.

*Compression Bar*

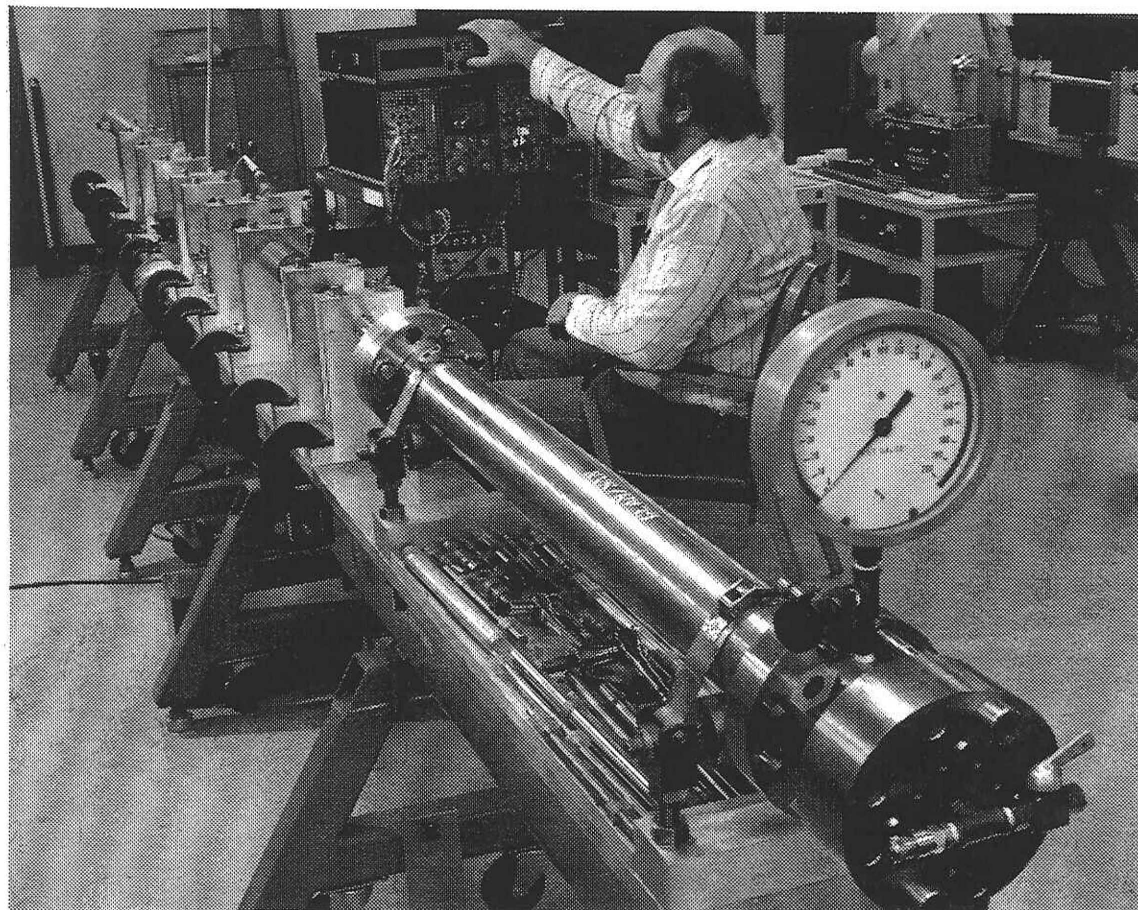


- Strain Rates up to 10,000/s
- Bar diameters: 3/8 to 1-1/2 inches
- Bar length, input and output, each: 48 inches
- Striker bars: 2 to 18 inches
- Tapered striker bars for pulse shaping
- Bar material:

  C350 maraging steel 350 ksi yield
- Ramp pulse modification
- Stress reversal capability:

  Compression followed by tension, and

  Tension followed by compression (with pulse trapping)
- Momentum trapping modification for single compression, or tension, or combined pulse



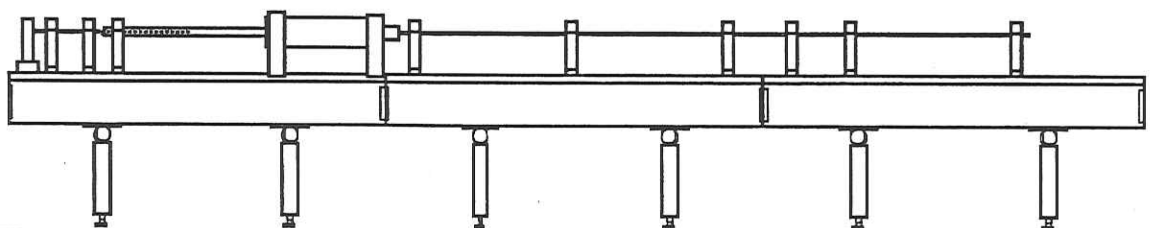
Compression Hopkinson Bar with Engineer Jon Isaacs Generating Stress-Strain Curve on Nicolet 4094B Digitizing Oscilloscope

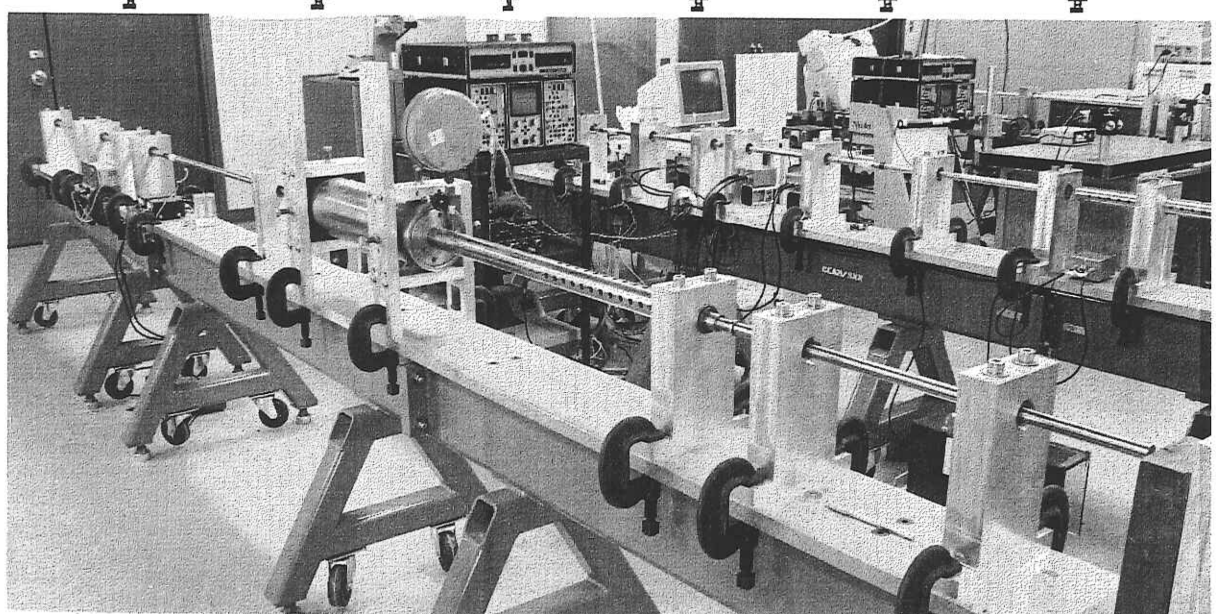
*Tension*

- Button end input bar, gas-gun-fired annular striker design
- 3/4-inch bar diameter
- Maraging steel and 17-7 stainless steel bar sets
- Momentum trapping modification for single tensile pulse
- Recovery of unfailed specimens loaded by a single pulse

*Compression-Tension*

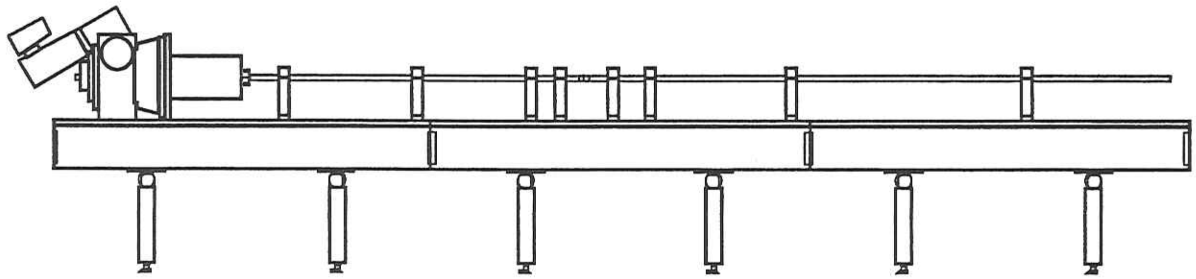
- Installed on either compression or tension bar platforms
- Single compression pulse followed by single tension pulse
- Recovery of specimens after a single load cycle
- Recovery of specimens after a single compression pulse



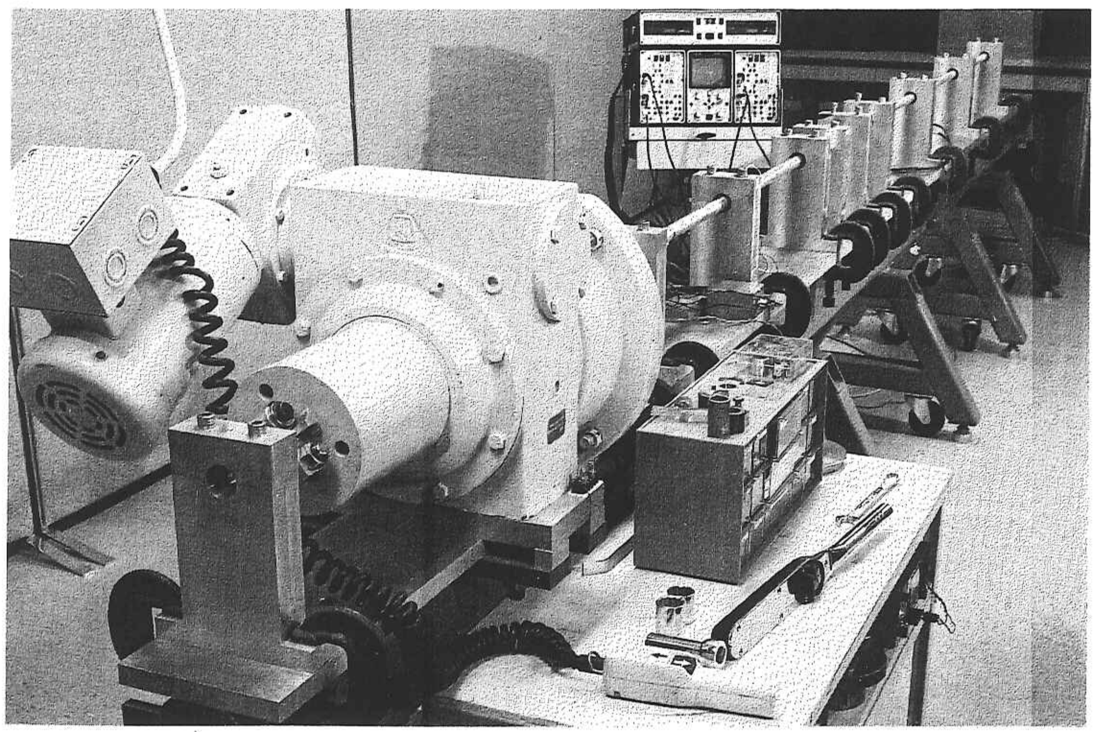


Tension Hopkinson Bar with Momentum Trap for Recovery Tests with a Single Tensile Pulse

*Torsion*



- Self-locking worm gear drive
- Precise, simple, pretorque and release mechanism
- Symmetric reaction torque
- Bending-free torsional waves
- Adaptable for multiaxial loading
- 1-inch diameter bar
- Variable pulse length

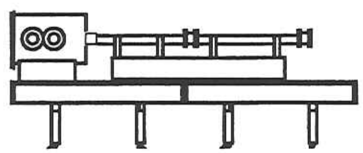


Torsion Hopkinson Bar with Pulse Width Modification

### *Gas Guns*

Gas guns are precision instruments for flyer plate and other impact experiments. The flyer plate experiments produce extremely high rates in exceptionally clean states of homogeneous strain. The Center's gas guns include a small, moderate-velocity instrument of 60-mm bore, and a large, high-velocity instrument of 56-mm bore.

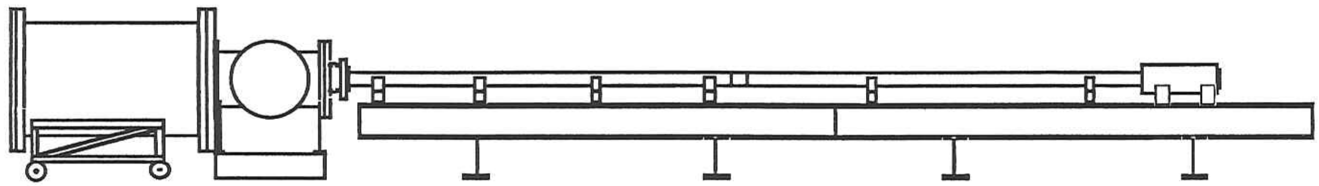
*60-mm Gas Gun*



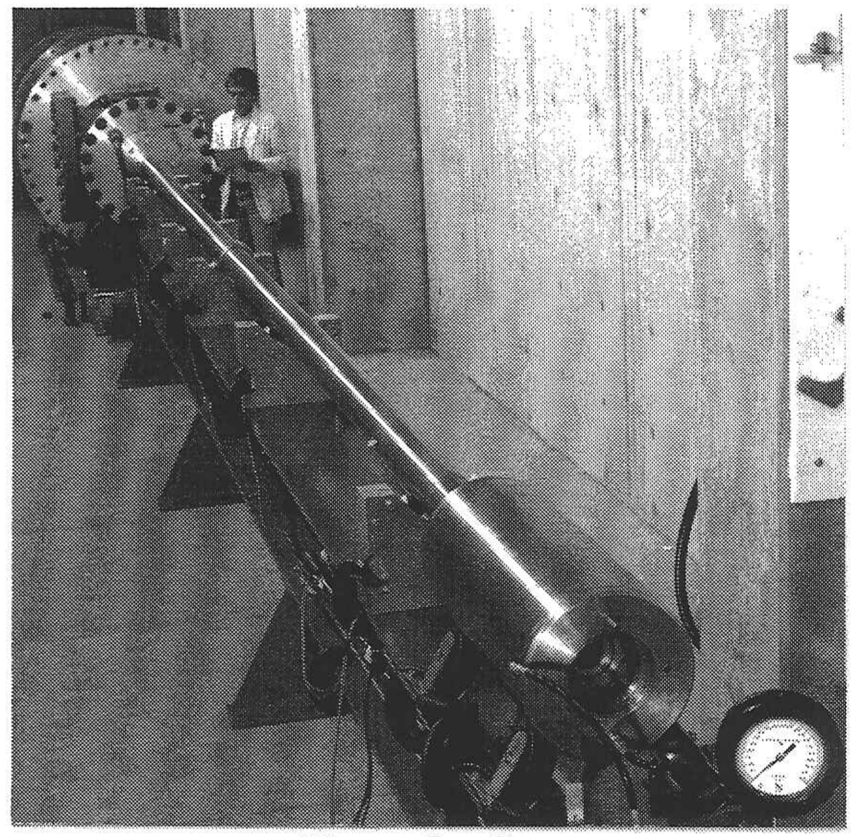
- Up to 200 m/s impact velocities
- Micro-grooved barrel
- Normal impact and pressure-shear experiments
- Momentum trapped recovery experiments
- Normal and transverse displacement and velocity measurements by interferometry


60-mm Gas Gun in Flyer Plate Configuration Operated by Graduate Student A. Machcha. Interferometry setup measures particle displacements and velocity of the back face of momentum trap, using Spectra-Physics 2020 argon ion laser.

*56-mm Gas Gun*



- Over 1,000 m/s impact velocities
- Plate impact experiments
- Sphere and rod impact geometries
- Soft recovery system
- Complete interferometric measurement systems
- Flash X-ray radiographic capability

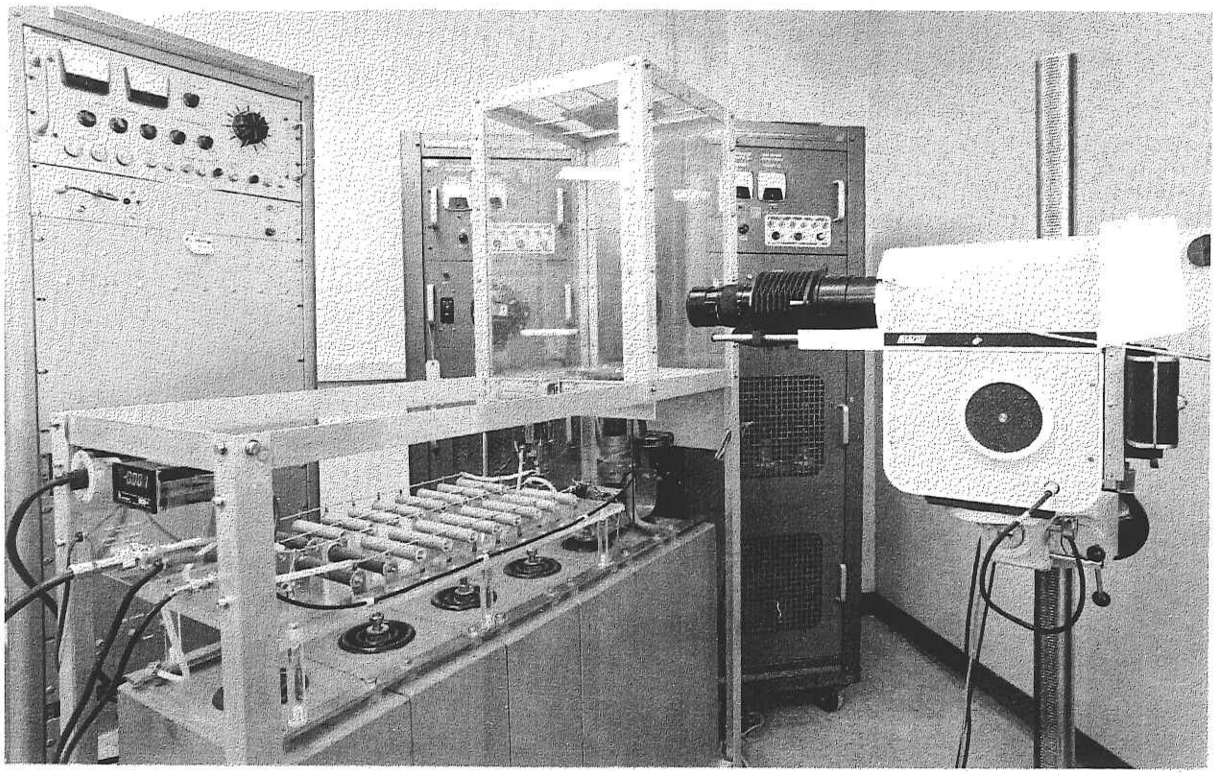


56-mm Gas Gun
Post-Doctorate M. Ahmadshahi checks data network at experimental end of the 56-mm gas gun

### *Electromagnetic Facility*

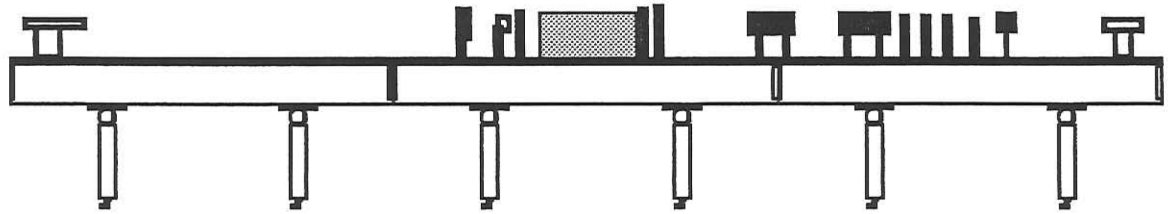
Electromagnetic techniques provide an alternative to mechanical methods of generating high loads and loading rates. These techniques have the special advantage of precise timing, which allows carefully coordinated loading events to produce analytically tractable states of multi-axial loading. The present apparatus is operated as an electromagnetic flyer plate launcher or, for radial loading, by changing the coil and transmission line geometry.

- 20-gram, 50-mm diameter flyer plates
- Velocities of 150 m/s with less than 1 kJ input
- Fast recycling of apparatus
- Capacitor banks in excess of 20 kJ available
- Ignitron switching in excess of 100 kA available



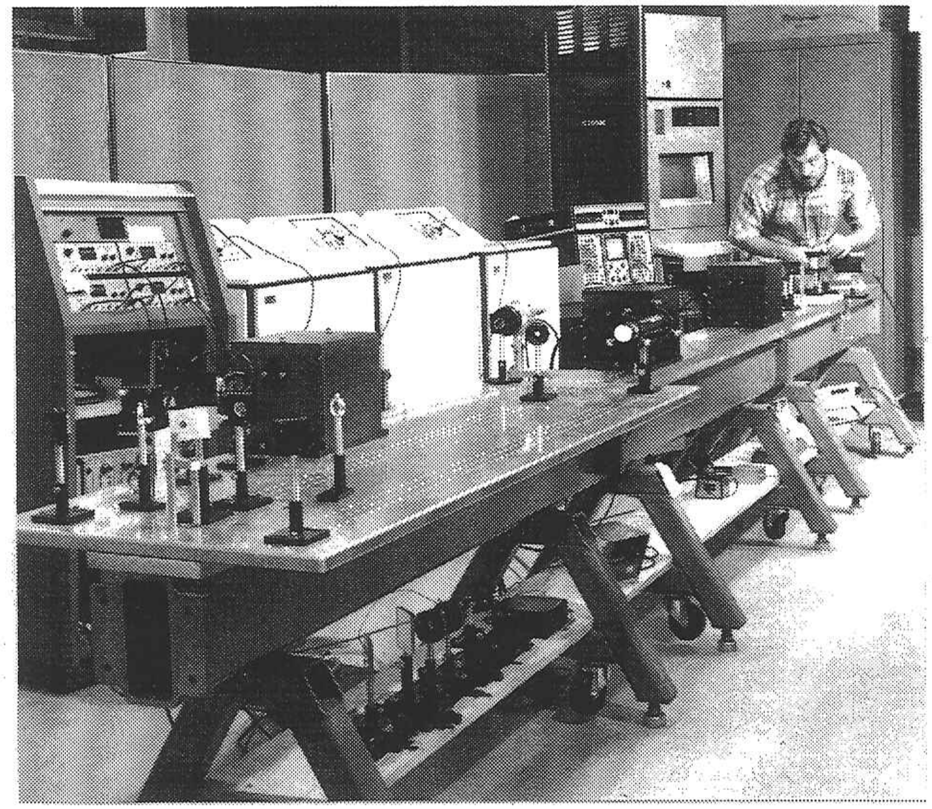
Electromagnetic Flyer Plate Launcher with
Hadland Imacon 790 Camera (at right)

### *Laser Impulse Facility*



This unique facility provides a dynamic probe for investigating phenomena such as the evolution of microcracking in brittle materials under high loading rates. Because of the precisely limited mechanical energy, specimens can be taken above failure thresholds and recovered intact for post-test characterization. The extremely short duration of the pulse makes it an ideal instrument for probing other very fast phenomena, such as stress-induced phase transformations.

- 10J Q-switched ruby laser system
- Laser pulses as narrow as 20 ns
- Stress pulse width as narrow as 100 mm (0.004 inch)
- Multi-GPa stress levels
- Short time-scale, plane-wave stress cells



Laser Impulse Facility Includes 3-Stage Ruby Laser System, Pulse Slicer, Stress Cell, and LeCroy 6880 and Nicolet 4094C High-Speed Digitizing Oscilloscopes. Capable of one billion-watt output, the laser impulse system undergoes final alignment by Engineer D. Lischer.

## III. Diagnostic Facilities

Image and data acquisition capabilities include cameras up to 20 million frames per second, X-ray flash photography, computer-generated holographic interferometry, and 1.7-GHz digital signal sampling.

*High-Speed Photographic Facility*

- Hadland Imacon 790

  20-million frame per second image intensifier camera

- Cordin 330A

  2-million frames per second, continuous access, 35-mm film high-speed camera

- Ellis Camera

  Million frame per second 35-mm film high-speed camera

- Ruby Laser System

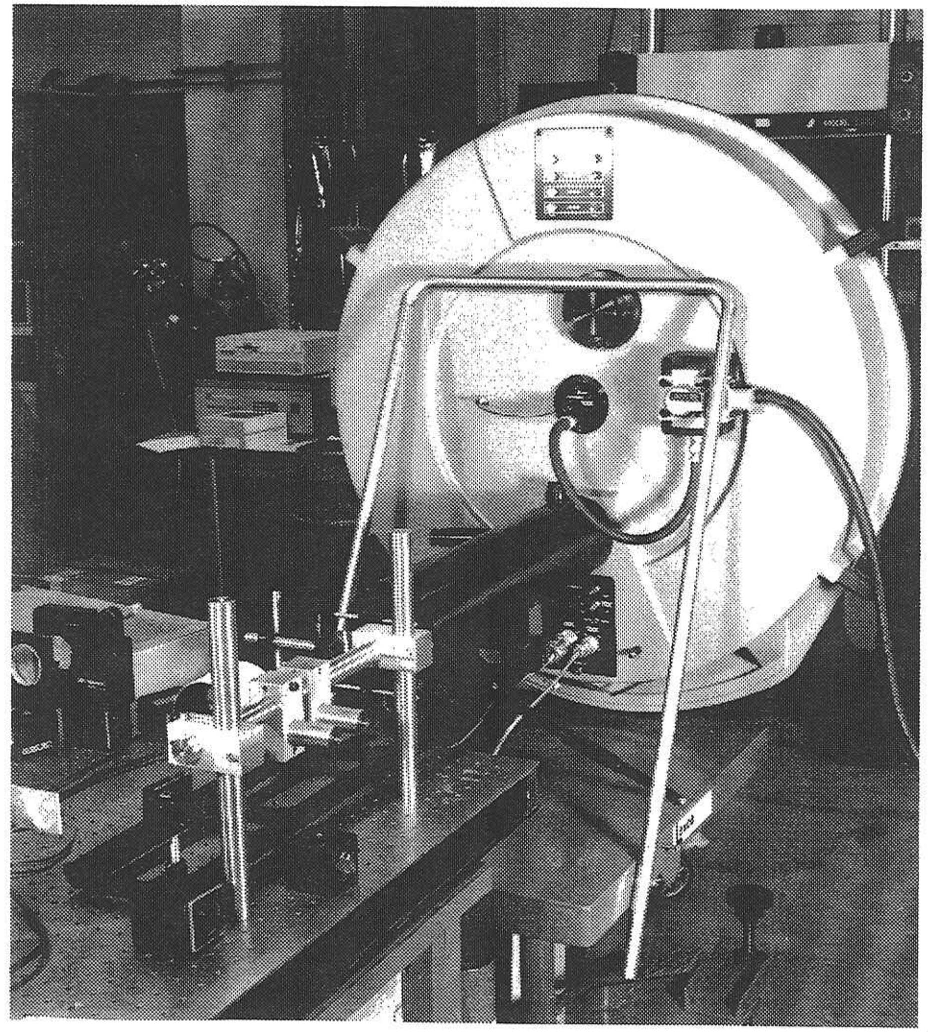
  Application specific pulsed laser light source

- Megawatt Flashlamp System

  Variable pulse duration, 4-megawatt xenon flashlamps

- Beckman and Whitley Drum Camera

  10,000-frame per second, rotating drum, 35-mm high-speed camera



Cordin 330A High-Speed Camera Configured for Holographic Interferometry

***Holographic and Optical Measurement Facility***

Four independent optical benches provide workstations for the two pulsed ruby laser systems and the two CW argon ion laser systems. These include:

Spectra-Physics 2020 Argon Ion Laser

Coherent Innova 70 Argon Ion Laser

1-Gigawatt Ruby Laser System

Application Specific Modulated Ruby Laser System

Real-Time Computed Speckle Holography

High Resolution Pulsed Laser Holography

Holographic Interferometery

***Optical Interferometry Facility***

Capabilities include normal and transverse displacement techniques and ultra-fast velocity measurements.

Displacement Interferometry

Velocity Interferometry

VISARS

Shearing Interferometry

***Flash Radiography Facility***

Two separate systems provide velocity measurements of gas guns and visualization of internal structure of materials.

150 kV Hewlett-Packard Flash X-Ray

450 kV Hewlett-Packard Flash X-Ray

*Image Processing Facility*

- Imaging Technology Series 151 Image Processor

  Computer-generated holographic interferometry for measurement of very small displacements

- Werner Frei Image Lab

  Computer analysis of material microstructure before and after recovery experiments or *in situ* measurement and observation

Graduate Student G. Subhash analyzes granular flow data for photoelastic granules on the portable image lab

***Digital Data Acquisition Facility***

Ten independent mobile workstations provide for acquisition, storage, and computer analysis of data.

- LeCroy 6880

  Two 11-bit/8-bit, 3-channel, 1.3-GHz digitizing oscilloscopes

- Nicolet 4094C

  One 8-bit, 4-channel, 200-MHz digitizing oscilloscope

- Nicolet 4094B

  Three 12-bit, 4-channel, 10-MHz digitizing oscilloscopes

- Nicolet 310

  Two 12-bit, 2-channel, 1-MHz digitizing oscilloscopes

- Sony/Textronix RTD 710

  Two 10-bit, 2-channel, 200-MHZ digitizing oscilloscopes

## IV. Quasi-Static Testing Facilities

Computer controlled hydraulics and multi-axial load frames provide state-of-the-art testing of materials under quasi-static loading. The large triaxial cell facility, fully computer controlled for the study of granular materials, is the only one of its kind.

- Axial-Torsional Testing

  110 kip Frame
  20 kip Frame
  Large Triaxial Cell

- Biaxial Testing

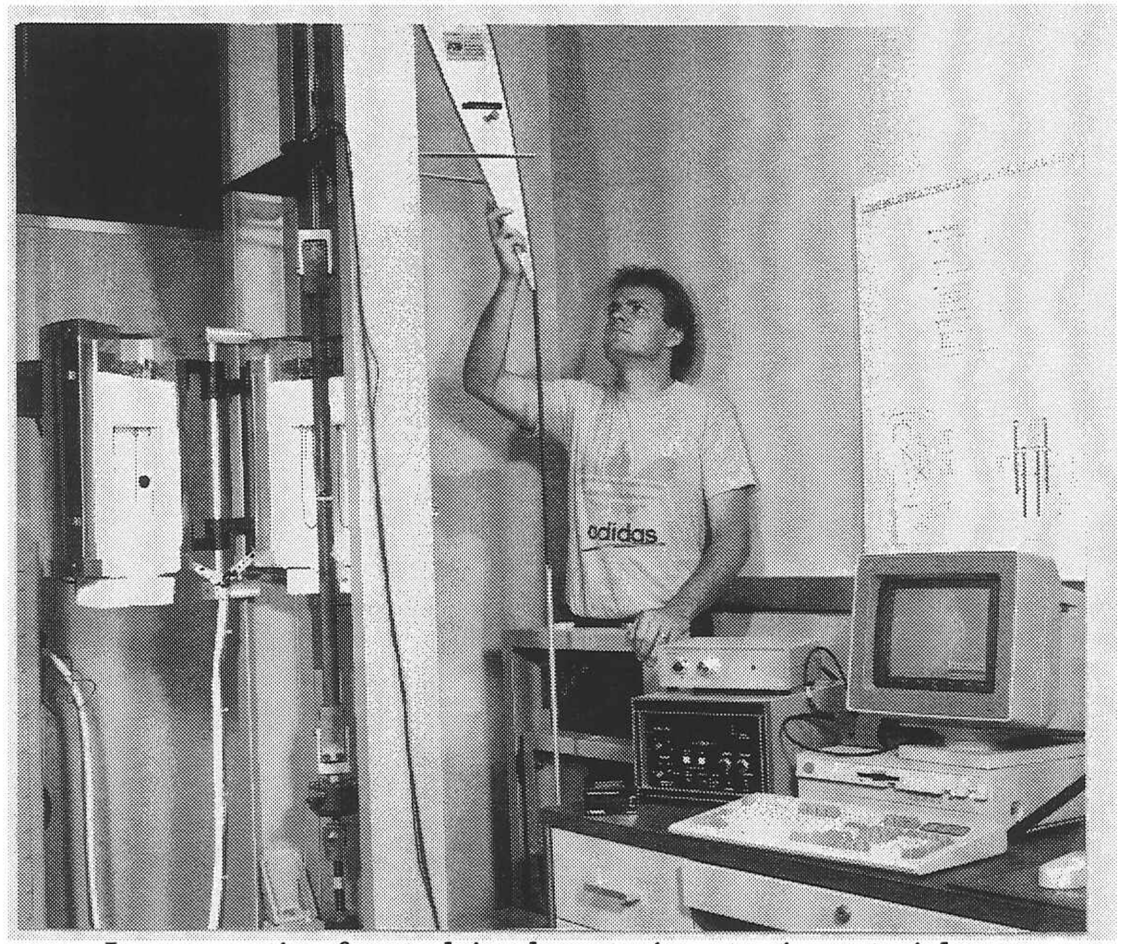
  Biaxial Frame
  Three 20 kip Frames

- High Temperature Testing

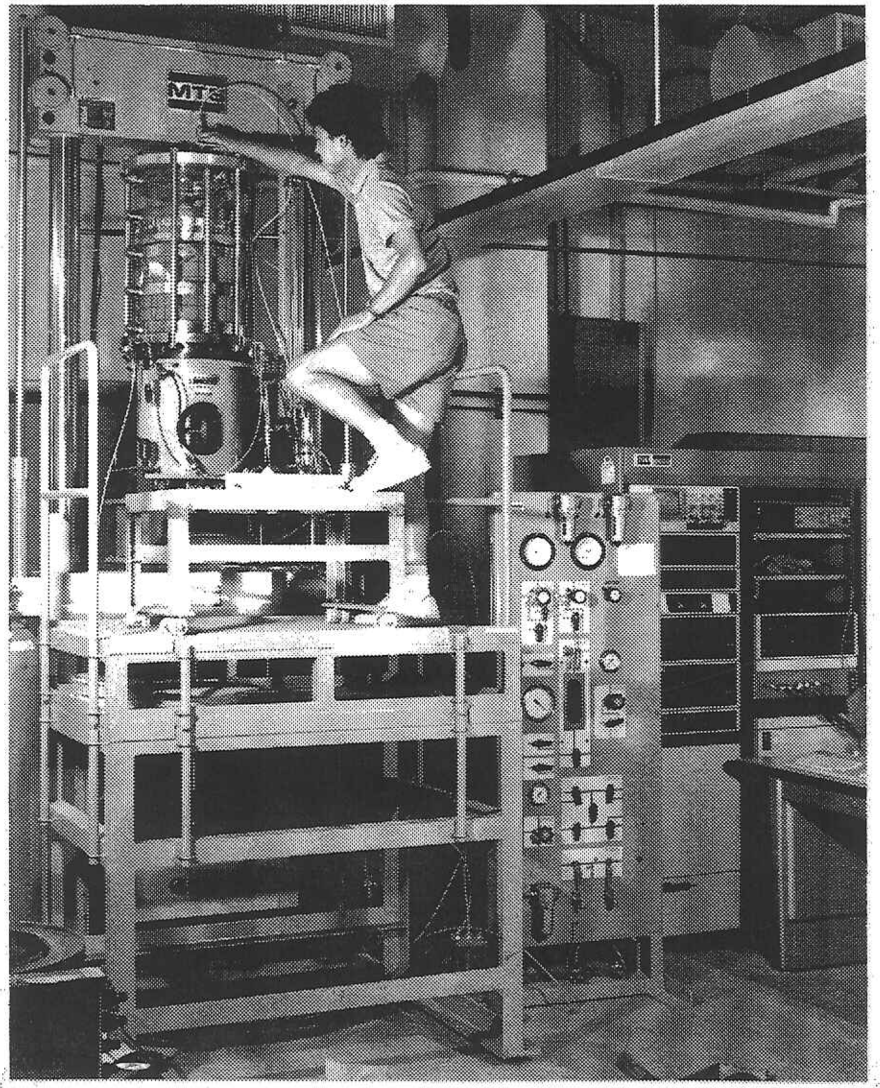
  Testing Furnaces
  Creep Machine

- Small Load Frames

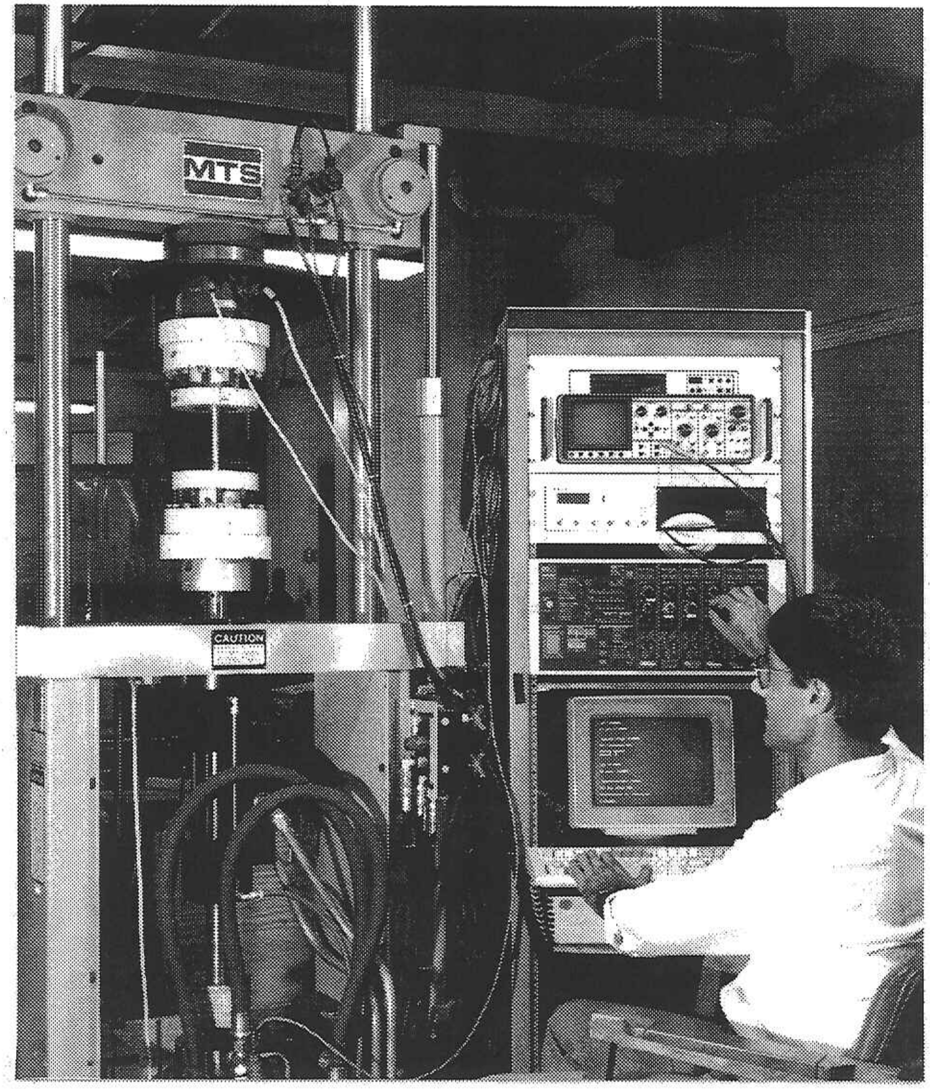
  Instron Screw Machines
  Fatigue Machine




In preparation for studying low-strain rates in materials at elevated temperatures, Graduate Student D. Owen checks the constant stress cam before starting a ceramic test in the Creep Facility




Studying properties of granular materials, Graduate Student N. Okada makes final preparations to the triaxial cell




Graduate Student A. Azhdari is calibrating the computer-controlled load cell on a 20-kip load frame with axial/torsional and biaxial capabilities

## V. Materials Synthesis and Processing Facilities

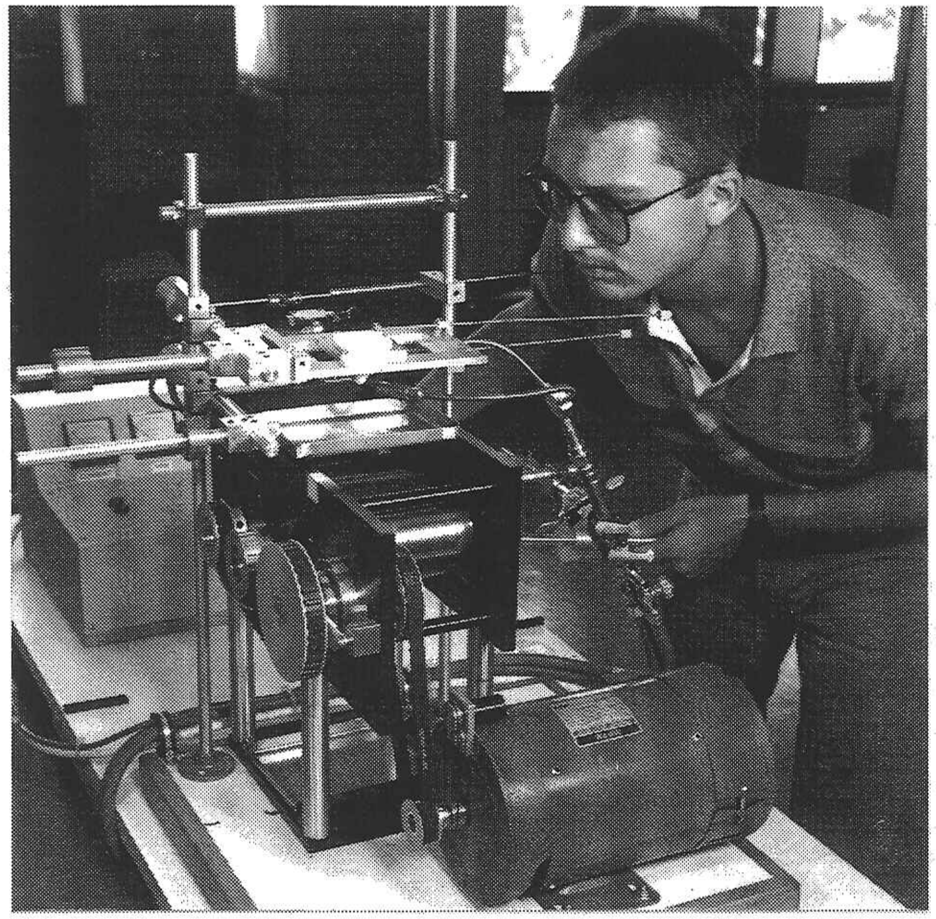
The CEAM facilities include equipment and machines for:

- rapid solidification
- chemical synthesis of oxide ceramics
- self-propagating high-temperature synthesis of non-oxides
- shock compaction
- high-impact forging

### *Rapid Solidification*

Rods of metals or ceramics are melted through induction heating or gas torches. The molten material is ejected through dual rollers rotating at surface speeds exceeding 16 m/sec. The capabilities of this facility are:

- quench rates greater than $10^6$ K/sec
- use of metals, ceramics, and particulate composite materials
- generation of metallic glass, oxide glass, and metastable crystalline phases
- generation of nanocrystalline materials



Undergraduate Student S. Emmenegger aligns a ceramic sample over the hydrogen torch before creating a novel material by rapid solidification

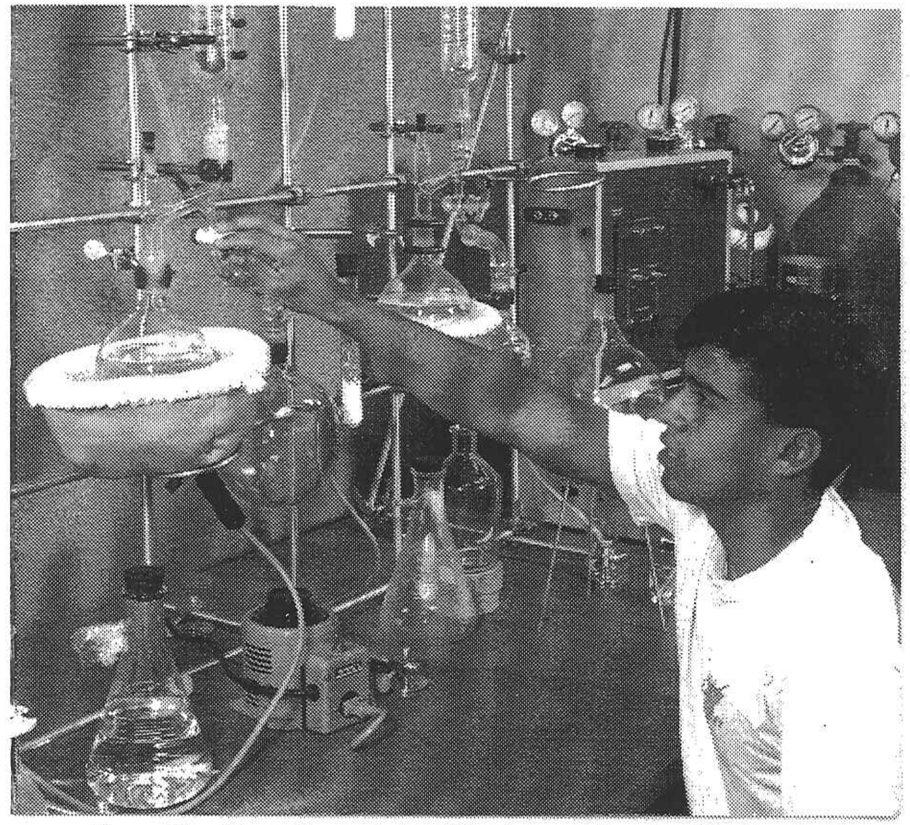
*Chemical Synthesis of Oxide Ceramics*

1. Alkoxide synthesis of amorphous powders

   - Dissolve ultrahigh purity metal in alcohol
   - Hydrolyze solution to precipitate hydroxide powders
   - Results in:
     - ultrahigh purity powders
     - extremely fine particle sizes
     - reduced sintering temperature
     - co-precipitation of two metal hydroxides to form a two-phase or composite material

2. Synthesis of films of $YBa_2Cu_3O_{7-x}$

   - Align thick (>10μm) films for optimal superconducting properties by spin coating organic solutions
   - Homogeneous, atomically mixed precursor gel
   - Easily controlled
   - Films can be spun on to complex shapes

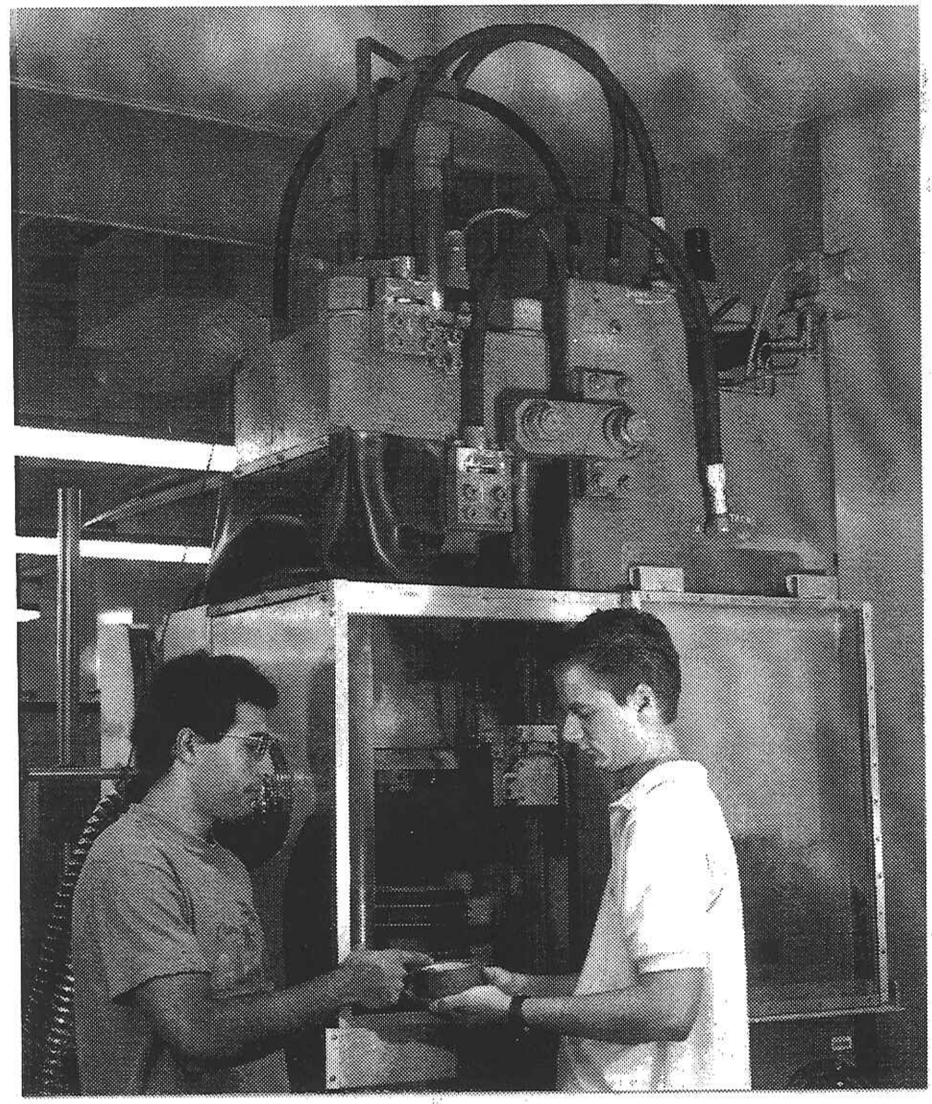


By adjusting flow rate, Undergraduate Student R. Contreras controls the process for synthesizing fine ceramic powders

## *Dynapak Facility*

The Dynapak is a high-energy rate machine for processing materials. The hammer derives the kinetic energy from compressed nitrogen gas (3,000 psi maximum pressure) and is propelled at velocities ranging between 10 and 20 m/s. The machine has the capacity of 20 strokes per minute. The maximum energy rating of the machine is 17 kJ. The ancillary equipment includes an environmental chamber, and heating and cooling furnaces. The machine has the following processing applications:

- dynamic forging
- dynamic compaction of porous ceramics
- dynamic extrusion of solids and powders

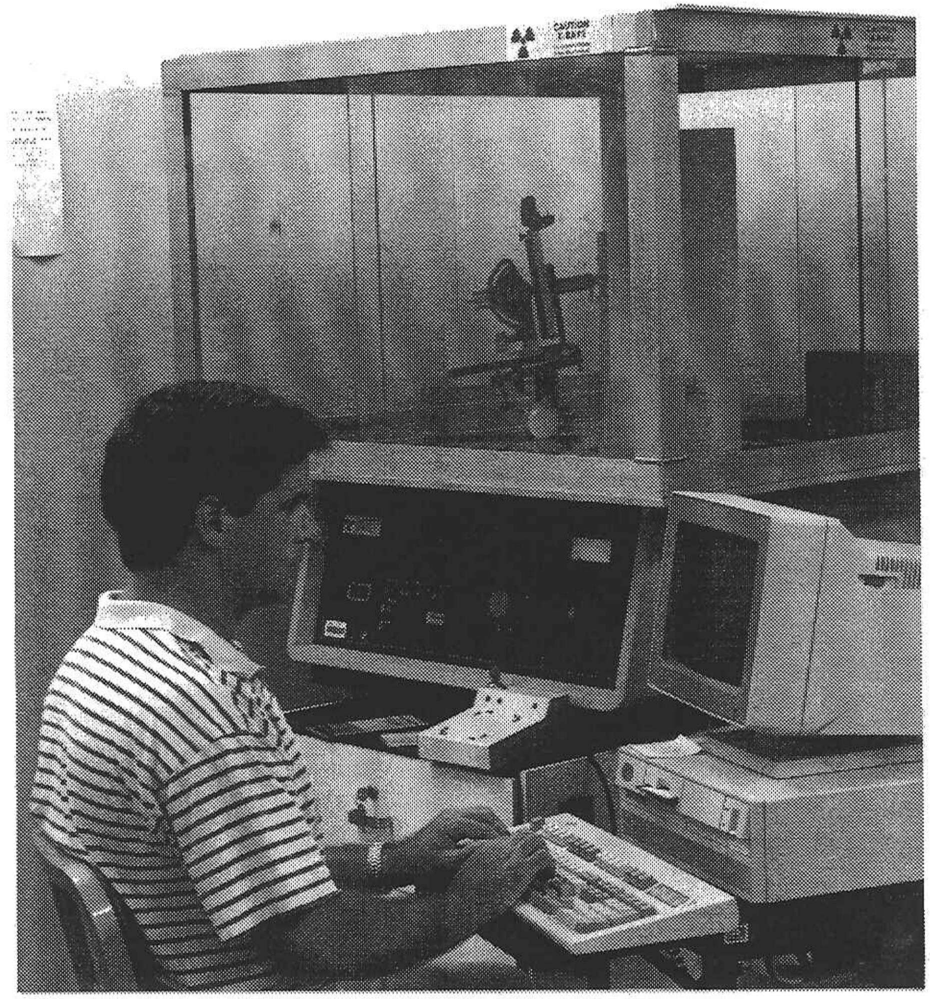


High-Velocity Forging System
A new ceramic material formed by dynamic compaction in the Dynapak Facility is being studied by Graduate Students J. LaSalvia and D. Hoke

## VI. Material Characterization Facilities

Analysis of materials is performed before and after subjection to a known loading history. Characterization studies are dependent on reproducible sample preparation and analyzing equipment quality.

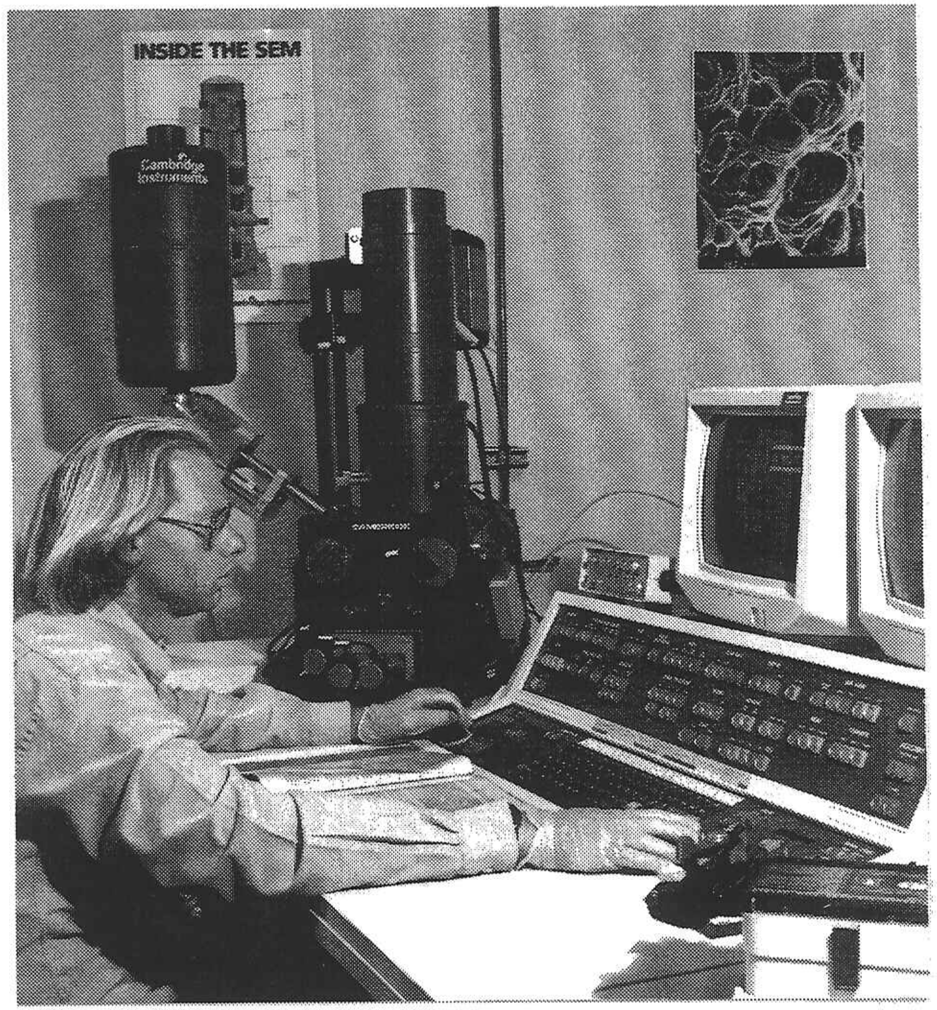
- Philips Analytical X-Ray System
    - Computer-Controlled Diffractometer
    - Laue Camera
- Ultrasonic Sound Velocity Measurement Facility
    - MATEC MBS 8000 Measurement System
    - Marconi 10-kHz to 1-GHz Signal Generator
    - Fully Computer-Based with Digital Sampling
- Nikon Metallographic Microscope
- Olympus Binocular Microscope
- Leco Microhardness Tester
- Quantasorb BET Surface Analyzer
- Perkin Elmer Differential Thermal Analyzer
- Sample Preparation Equipment



Post-Doctorate M. Rashid programs the computer-controlled x-ray diffractometer. (Laue camera shown mounted behind leaded windows by x-ray system.)

Division of Engineering Electron Optics and Microanalysis Facility

- Cambridge Stereoscan 360 Scanning Electron Microscope with an integrated Link AN10000 X-Ray Analysis System
  - Fully computer-controllable
  - Point-to-point resolution of 2.5 nm
  - Quantitative, semi-quantitative, or fully-quantitative compositional analysis on 1-micron scale range
  - Secondary and backscattered electron detectors
  - Accelerating voltages between 200 to 40,000 volts
- Philips CM30 300kV Transmission Electron Microscope with a Link AN10000 X-Ray Analysis System.
  - Fully computer-controllable, high-resolution, intermediate voltage instrument for high-spatial resolution X-ray microanalysis
  - Accelerating voltages between 50 kV and 300 kV
  - Ultimate resolution: 0.18 nm line-to-line<br>0.23 nm point-to-point
  - High-spatial resolution X-ray microanalysis on elements down to beryllium on periodic table
- Special TEM specimen holders include:
  - low-background single-tilt holder for microanalysis
  - double-tilt low-background holder for diffraction and microanalysis
  - liquid nitrogen low-background double-tilt holder with controllable temperatures from 100°C to -170°C
  - single-tilt furnace holder capable of 1,300°C




Students are trained in system operation to facilitate the time-consuming search for material attributes. Shown here, Graduate Student/Fellow B. Altman follows the start-up procedures of the scanning electron microscope in preparation for specimen viewing.

## VII. Specimen/Equipment Fabrication Facilities

- Powder Facilities
  - Glove Boxes
  - Mixers
  - Ball Mills
  - Presses
- Furnaces
  - Tube Furnaces
  - Muffle Furnaces
  - Vacuum Oven
- Materials Science Machine Shop
- Division of Engineering Machine Shop
- Upper Campus Machine Shop
- Glassblowing Shop